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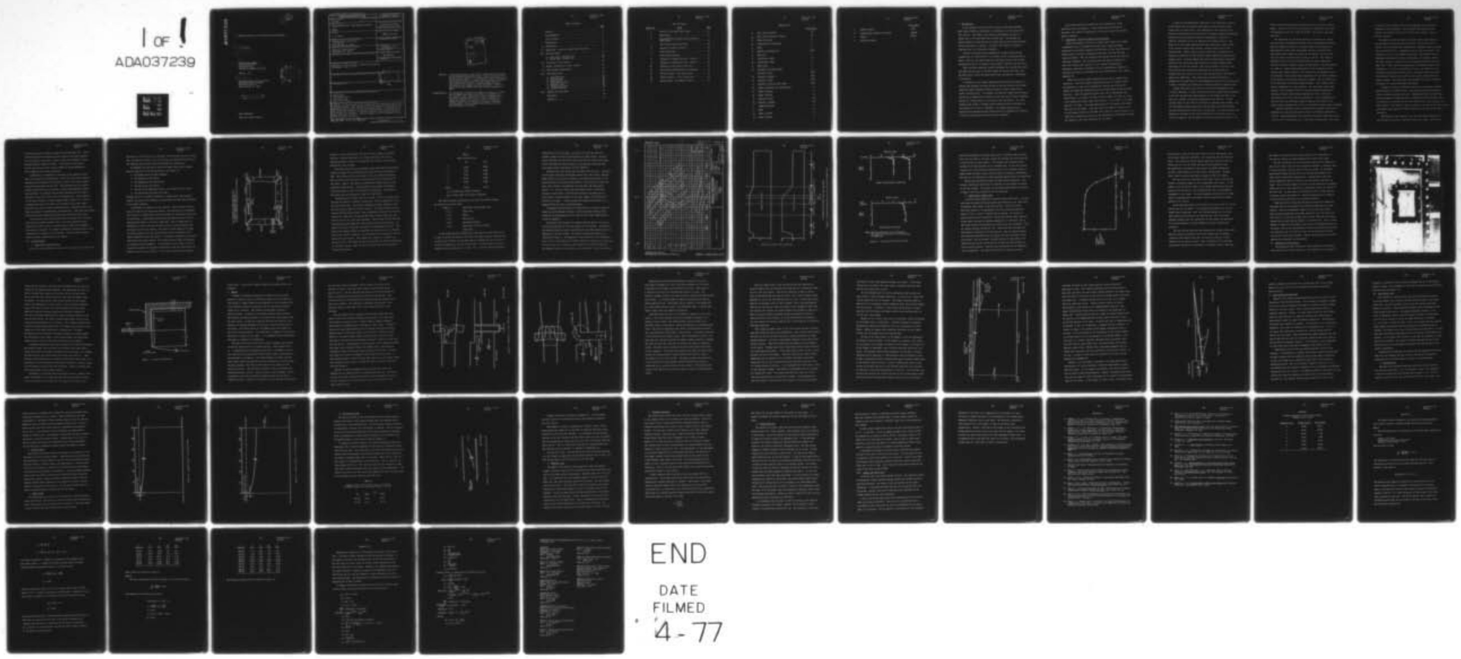

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A proposal was made to build a free surface flow test facility at the Garfield Thomas Water Tunnel. This facility was to be built by the conversion of the rectangular test section of one of the existing tunnels. As the project was begun a literature search was conducted to determine the state-of-the-art of free surface test sections. A testing program was then initiated and some design ideas were considered. This is a report of all the relevant work that has been completed to date.

Abstract: A proposal was made to build a free surface flow test facility at the Garfield Thomas Water Tunnel. This facility was to be built by the conversion of the rectangular test section of one of the existing tunnels. As the project was begun a literature search was conducted to determine the state-of-the-art of free surface test sections. A testing program was then initiated and some design ideas were considered. This is a report of all the relevant work that has been completed to date.

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Nomenclature

		F-L-T Units
A	area, cross sectional	L^2
A_o	area, cross sectional, original	L^2
b	width of channel	L
C_c	coefficient of contraction	---
d	depth	L
g	gravity, acceleration of	L/T^2
h	head loss	L
M	coefficient, shape	---
N	coefficient, shape	---
P	depth ratio	---
P_c	perimeter at critical depth	L
	pressure, cavity	F/L^2
P_o	pressure, original	F/L^2
Q	quantity of flow	L^3/T
q	quantity of flow per unit width	L^2/T
R_c	radius, hydraulic, at critical depth	L
S	slope of channel	---
S_c	slope, critical	---
V	velocity of flow	L/T
V_o	velocity, original	L/T
x	length downstream	L
y	depth	L
y_c	depth, critical	L
y_o	depth, original	L

		F-L-T Units
γ	density (force)	F/L^3
θ	surface angle relative to vertical	degrees
ρ	density	FT^2/L^4
σ	cavitation number	---

I. Introduction

A test section of one of the water tunnels at the Garfield Thomas Water Tunnel (GTWT) was considered for conversion to a free surface flow test facility. The present test section is rectangular in shape, 30 inches long, 4 1/2 inches wide and 20 inches deep. The maximum test section velocity is about 80 feet per second and the test section pressure can be varied from 3 to 60 psia. As much of this range of operating conditions was to be retained as possible.

In order to preserve the two dimensional, closed conduit testing capabilities, all modifications to the tunnel should be semi-permanent in nature. That is, the tunnel should be convertible from its free surface configuration back to its present closed channel condition, and vice versa.

This conversion capability should be designed into the modified tunnel. Switching from one mode to the other should not involve more than a few man hours worth of work and should entail only the removal or replacement of key pieces.

In addition to the hardware modification that would be necessary to initiate and terminate the water surface in the test section, this project would also entail subsystem changes necessary in order to make this a useful testing facility. For example, the hydrofoil balance which measures the forces on shapes which are placed in the test section flow is presently mounted in a fixed position on the side of the test section. In a free surface water tunnel, a variable position balance would be desirable, so the mounting of it must be redesigned. The tunnel pressure control system and the degassing system piping would not be adequate for operation in the free surface mode and these must be redesigned.

Any systems which must be added due to the existence of a free surface must also be designed. A water level control system may be necessary, and a means of supplying air to the test section free surface would be required.

II. Background: Other Free Surface Test Facilities

Before the design of the new free surface water tunnel was to begin, a background study of existing free surface water tunnels was made. Information was obtained primarily from facilities of this type within the United States, because the information from these facilities was more readily available. What was available from foreign sources was often not published in English. The test facilities from which the majority of data were obtained were located at 1) St. Anthony Falls Hydraulic Laboratory, University of Minnesota [1,2]; 2) Hydrodynamics Laboratory, California Institute of Technology [3]; and 3) Hydronautics, Inc., Laurel, Maryland [4].

There were two very useful publications from the St. Anthony Falls Laboratory. The first primarily explained what type of features would be desirable in a soon to be designed free surface test facility [1]. Before the design was completed however, a 4.8 scale model of the new tunnel was built. Since the proposed facility was to be of considerable size (test section: 3 ft wide, 6 ft deep, and 25 ft long), the model of it was a fair sized water tunnel itself (test section: 7.5 in. wide, 15 in. deep, and over 4 ft long). The second publication [2] is a report on the shake-down tests of this model. Since the size of the model is closer to that of the proposed facility at the GTWT, these data are of more interest to us than those concerning the prototype. The information in this report concerns all aspects of the tunnel design and is very useful.

A report on the Hydrodynamics Laboratory at the California Institute of Technology (CIT) [3] contains a few pages on the free surface water tunnel which is located there. The information on this facility is not present in such volume but some details of the tunnel's design and operating characteristics are presented along with information on some of the important subsystems such as air separation and pressure control. One aspect of the CIT tunnel operation which isn't mentioned in this article is the surface boundary layer problem. Boundary layers exist in all flowing fluids. However, where a quick contraction is encountered, the resulting acceleration of flow velocity usually temporarily minimizes the boundary layer. Personal communication with the Hydrodynamics Laboratory indicated that they had had some problems with a large boundary layer continuing into the test section. This was particularly critical on the water surface where the velocity difference was so great that the boundary layer was visible to the eye, and the distortion of the velocity profile was significant. This problem has since been corrected by skimming off the upper layer of fluid immediately before the test section [5]. A report concerning this problem and its solution should be available soon.

Another free surface test facility is located at Hydronautics, Inc. of Laurel, Maryland. A report on this facility [4] contains some information on the size and operating characteristics of the channel, but most of the data in it concern the testing capabilities of the facility. A visit was made there in July 1975 for the purpose of observing their channel. One of the possible problems mentioned by the personnel there centered about the vena contracta which forms after a sluice gate. In a vena contracta, the decrease of the depth of flow can be significant, but in this case it is much less important than the length of the test section used up by it. The

flow in the test section must be uniform to be of any use as a testing medium. Until the end of the vena contracta is reached the water depth is decreasing and the flow cannot be uniform. More will be said about this later.

An interesting but irrelevant reference is available on a Danish testing facility considerably different from the type proposed here [6]. Ship hull shapes are tested in a situation where the free surface is represented by a metal plate surrounding the hull at the water line. Even though surface models are tested in this tunnel, this is not the true free surface condition which we hope to achieve. This report is mentioned because it was discovered through the use of computerized literature searches conducted through the ARL Library. Two such searches (1. NASA, 2. Defense Documentation Center) were conducted for free surface water tunnel literature. The results were two impressive lists of references. However upon closer examination, not one useful reference on the design of free surface facilities resulted. This is probably due to the narrowness of the field being researched. Such a limited topic was not catagorized for search purposes. For that reason a more broad catagory, "Water Tunnels," had to be used and references dealing with all types of water tunnel testing programs were cited. None dealt specifically with free surface test facilities. It was interesting to note that even the references already on hand were not listed in the search results, although they did fit in the general catagory being researched.

Sketchy information, such as dimensions and attainable velocities, is available on a big circulating water channel at the Berlin Model Basin [7,8,9]. These publications are interesting for general background information but aren't very helpful, due to their lack of design data. The tunnel

in Berlin is of an enormous size and not comparable to the facility proposed for this laboratory. More technical publications on this facility are available [10,11] in the water tunnel library. They are written in German.

Two papers are also available on the free surface water tunnel at the University of Grenoble in France [12,13]. Both of these are in French. One of these has been translated by a graduate student in French here at Penn State [14]. A typewritten copy of this is available. The translation is not of the highest quality due to the student's lack of knowledge concerning the technical terminology. For example, wherever the word 'profile' is used the correct translation would have been the word 'foil.' Other such misinterpretations are probably present in the translation. If it is to be referred to for use, the presence of such terminology difficulties should be noted. The paper covers the results of some tests conducted at the facility but is not concerned with the tunnel's design. The second paper from Grenoble [13] was not translated but appears to contain more design information.

A project to convert an existing tunnel into a free surface facility had been begun at the GTWT in 1971. Some design data could be obtained from the studies and plans made then. Unfortunately when this particular plan was dropped no attempt was made to document what had been done. What is available is in the form of some notes which are not very extensive, and some drawings. They should at least be looked at, but most of the notes concern now obsolete price quotes for various components to be used in the tunnel conversion.

The proposal at that time was to do the free surface conversion to the circular test section of the twelve inch water tunnel. Most of the

conversion plans were complete through the drafting stage [15]. Since the plans deal with a different facility than the one being considered now, the design is not usable. However, some of the auxiliary system designs should be looked at closely. In particular, the pressure control and the water level control systems are easily adaptable to the rectangular test section conversion.

A great deal of information is available on the present facility which was considered for modification. One of the most useful contains drawings and descriptions of the tunnel's circuit, test section, pump, structure and auxiliary systems [16]. Also presented are the tunnel's present capabilities such as pressure, velocity and temperature ranges. Less organized, but possibly more detailed information of this type is available in the tunnel files and in the drawing files. Also available in the tunnel library is a copy of Roger Steele's thesis [17]. This is a design thesis and is the basis for the design of this water tunnel. This was not as good a source of information as it should have been since there were quite a few mathematical inconsistencies. These were particularly noted in the section dealing with head losses around the tunnel loop.

If the resuts of any calculations made in the thesis are to be used, they should be checked carefully first. The thesis discussion deals primarily with the circular test section and at times the rectangular test section is ignored. For example, estimates of the head losses in the rectangular test section are not even made. The thesis does, however, contain valuable information about the tunnel.

III. Testing Program

a. First Tests, September 1975

The first testing program was conducted in the tunnel in September 1975.

The purpose of these tests was to determine the head losses around the tunnel loop, the velocity profile in the test section, the pressure distribution in the approach nozzle and how these are affected by a free surface.

To determine the head losses around the tunnel loop, static pressure taps were placed at the following locations (see Figure 1):

1. The upcomer above the heat exchanger.
2. The beginning of the nozzle.
3. The beginning of the test section.
4. The end of the test section.
5. The end of the horizontal diffuser, just before the first turn.
6. The bottom leg, just before the pump.

Through the use of a pressure transducer, a stepper valve, and a digital readout, the pressure was measured at these points with the tunnel operating in its normal condition.

To determine the effects of a free surface, a few very minor modifications were made to the tunnel test section. The ceiling of the rectangular test section is 2 inches higher than the ceilings of the approach nozzle and of the diffuser. Under normal tunnel operating conditions there are false ceiling pieces which fit into this raised area. Each of these pieces is fastened to the top of the test section by four set screws located on the top exterior of the test section. The effect of these pieces is to bring the ceiling height of the test section down to match the heights of the tunnel immediately before and after it. To achieve a makeshift free surface these pieces were first removed. The tunnel was then filled, and operated at a pressure below atmospheric. A tap located in the ceiling of the test section was opened, and the pressure difference forced air from outside the tunnel to enter the test section. If the tunnel velocity was low enough,

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● o -Location of static pressure taps
o - Used to determine head loss
● - Used to determine pressure profile of nozzle

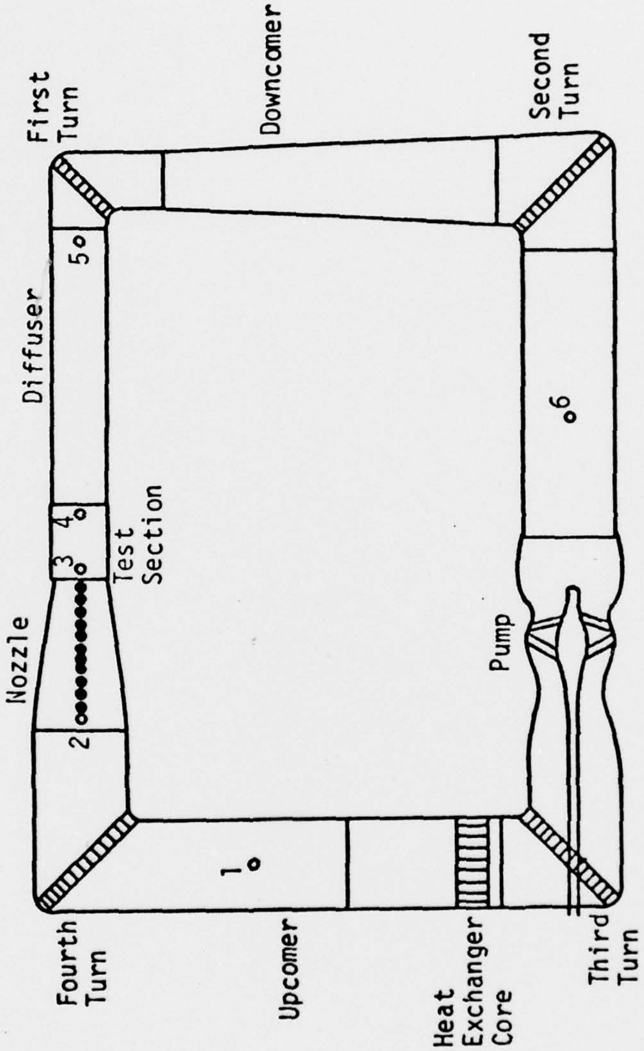


Figure 1 - Circuit of the Small Water Tunnel [16]

enough air could collect inside the test section to enable an air/water interface to become established. At higher velocities, the air was washed downstream as fast as it entered the test section, and no surface measurements could be made.

Once free surface flow was stabilized, head losses were again measured around the tunnel loop to determine what effect the free surface had on them. The presence of the free surface in the test section should have had no effect on the head losses in the lower leg and in the upcomer of the tunnel. However, the head loss coefficients obtained under the two conditions compare poorly. The head losses were measured by comparing total head values at each of the pressure tap locations. (See Figure 1) The values were then converted to head loss coefficients.

Unfortunately the results were not too good. Much of the error could have been the result of velocity fluctuations. This was especially true in the free surface mode. The velocity readings were quite unstable as were the water surface levels in the test section. As velocity changes so does pressure and thus pressure head. Since simultaneous velocity head readings could not be taken with the pressure head data, average values were used for this part of the total head throughout. Thus average velocity head and fluctuating pressure heads were used to obtain the total head losses. In spite of the poor correlation, the results are summarized in Table I. The head losses between pressure tap locations are presented not as a function of the local velocity head, but all are presented as a function of velocity head in the test section. This enables the k values to be summed over the entire loop. This would not have been possible had each been referenced to the local velocity, since the local velocities vary due to changes in cross-sectional area.

TABLE I

Tunnel Loop Head Loss

	K_n	K_{FS}
1		
	0.021	0.006
2		
	0.011	0.005
3		
	0.017	0.062
4		
	0.163	0.385
5		
	0.006	0.020
6		
Total	0.218	0.478

K_n = K value under normal conditions

K_{FS} = K value under free surface conditions

The tunnel elements contributing to the head loss between pressure tap locations are listed below.

Pump to 1	Third Turn, Heat Exchanger Core
1 to 2	Fourth Turn
2 to 3	Nozzle
3 to 4	Test Section
4 to 5	Horizontal Diffuser
5 to 6	First Turn, Vertical Diffuser, Second Turn

It had originally been intended that these head loss coefficients would be used to obtain head losses to be used in the power equation, Power=$Q\gamma h/550$. By solving for velocity, it was hoped that the maximum test section velocity could be determined for the free surface mode. The calculation for present maximum velocity would serve as a check. Due to the poor comparison between

coefficients for the two modes, it was not felt that the data were reliable enough to justify the publication of these results. The pump curves from which the efficiency values necessary for these calculations must be obtained are found in Figure 2, and with more consistent head loss figures these calculations could be completed.

Qualitatively a few things were observable from the tests. Locations in the tunnel loop where the greatest losses occur can be seen. Whether under normal or free surface conditions, the greatest proportion of the head loss occurs in the horizontal diffuser. The results also show that when a free surface is established, the area where the free surface exists, i.e., the test section and the diffuser, shows a significant increase in head losses. The differences between the normal and the free surface k values computed for the other regions of the tunnel are difficult to justify. If more reproducible figures are desired, it is suggested that the tests be performed again.

A graphical representation of the head losses as computed around the tunnel loop is presented in Figure 3, and the pressure readings taken during the testing program that were used in the k value computation are listed in Appendix I.

During this test program, the vertical velocity profile in the test section was measured both with and without the free surface. The profile was measured along the tunnel centerline about ten inches downstream of the beginning of the test section. The results of these measurements are presented in Figure 4. The magnitude of the velocities is not significant here, but it is the shape of the velocity profile in which we are interested. As can be seen from the figure, under normal closed channel conditions, the boundary layer was very distinct, but fairly small. After free surface

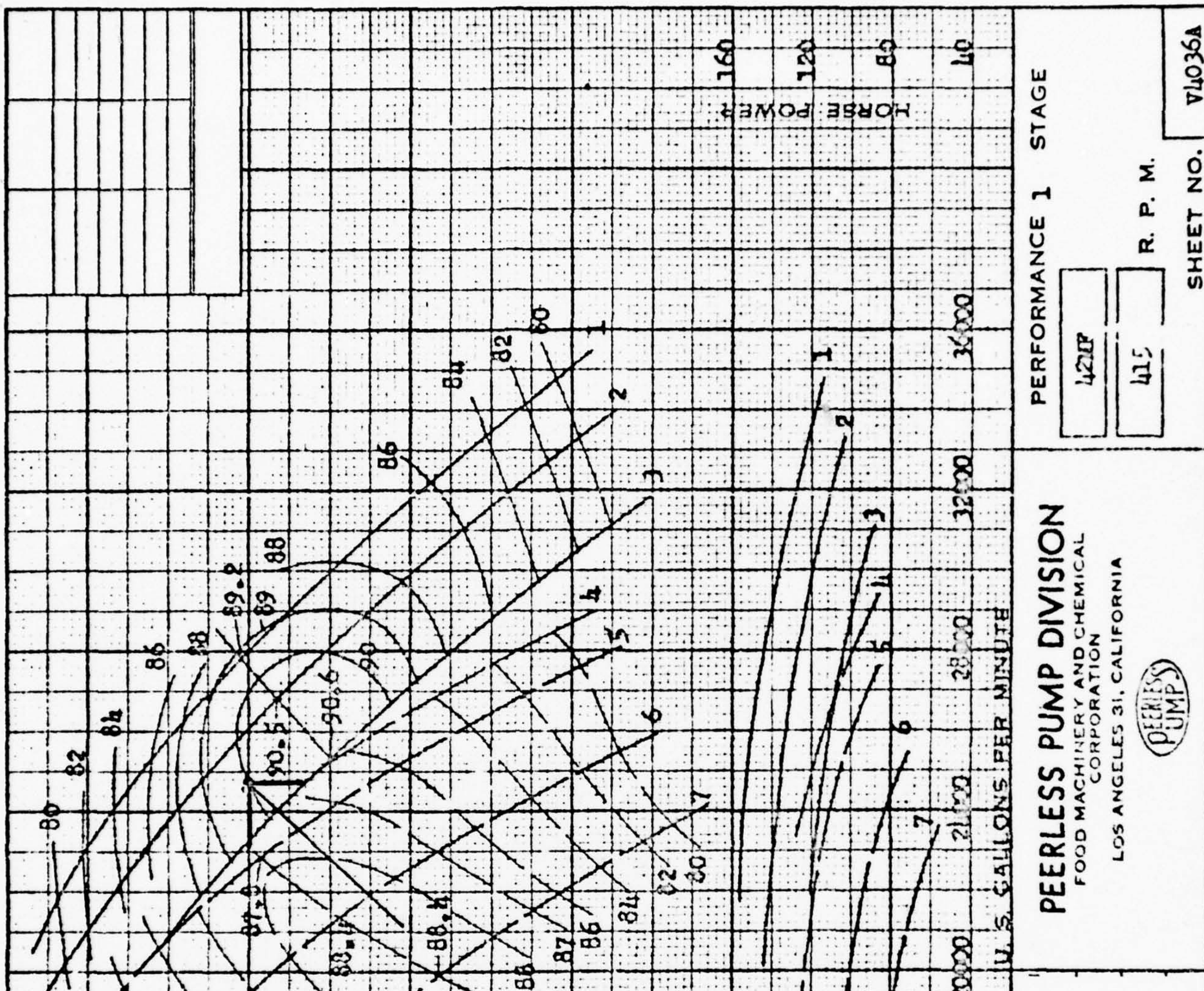


Figure 2 - Pump Curves

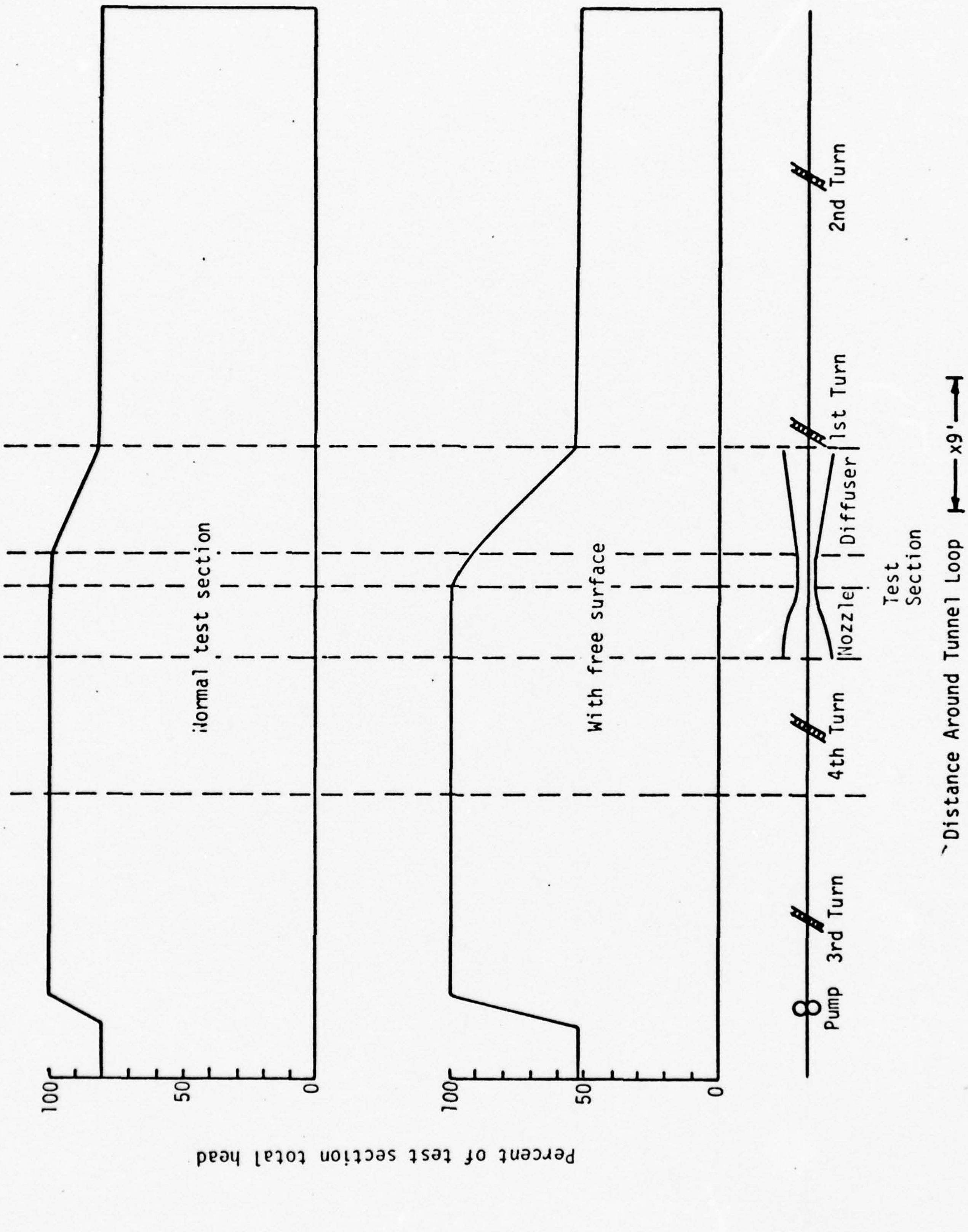
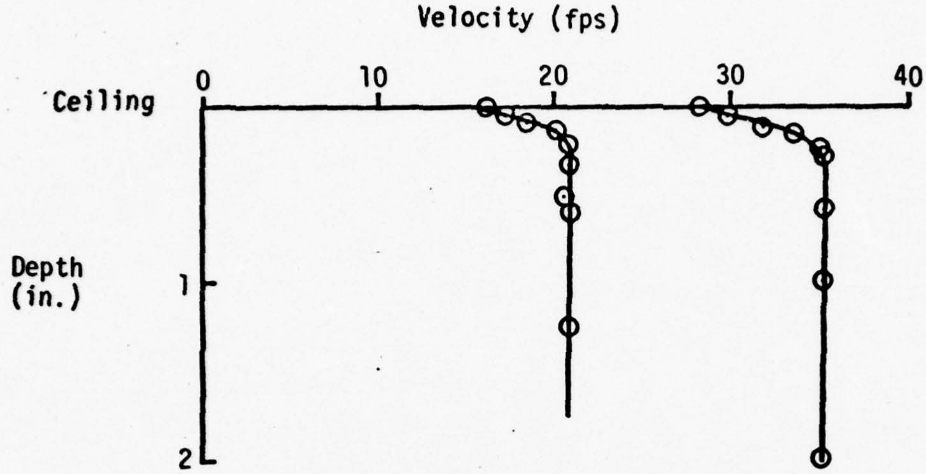
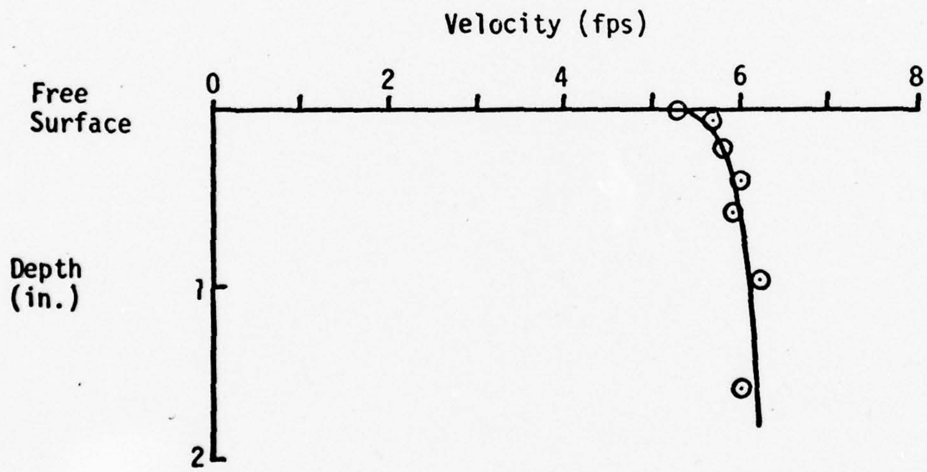


Figure 3 - Nondimensionalized Energy Lines Around the Tunnel Loop



Normal closed-channel conditions



Free-surface conditions

Note: Velocity magnitudes are not important.
The shapes of the profiles are the subjects
of comparison.

Figure 4 - Test Section Velocity Profiles

flow was established the boundary layer wasn't so distinct and relatively thin, but even right at the water surface the velocity was still about 87% of the mean test section velocity. The boundary layer situation which existed at CIT would probably not be a problem here. In the free surface configuration, the profile was measured only at a low velocity because at higher speeds the water surface elevation began to fluctuate considerably. This made it very difficult to firmly establish exactly where the surface was.

The pressure distribution along the nozzle was also measured. This pressure distribution should not be a function of the presence or absence of the free surface. The results of the pressure measurements are plotted in Figure 5 and they coincide for the two conditions.

b. Second Tests, October 1975

A second testing program was conducted during October 1975. In these tests some stationary sluice gate pieces were inserted in the tunnel flow to determine their effect on the water surface. The sluice pieces which were mounted at the beginning of the test section had effective depths of 0.25, 1.5 and 4.5 inches from the ceiling. The results of these tests were also inconclusive. The primary surface effect observed during these tests was the upstream progression of a hydraulic jump as the tunnel velocity was increased, but results were not repeatable. There are several possible reasons for this. These tests were run under the same pressure conditions as the previous set. That is, tunnel pressure was taken below atmospheric and air taps at the top of the test section were opened. This is probably a significant part of the problem. The tunnel pressure control system will try to keep the tunnel pressure at the set control pressure. With the test section open to the atmosphere, this is impossible. The control system tries to reduce the tunnel

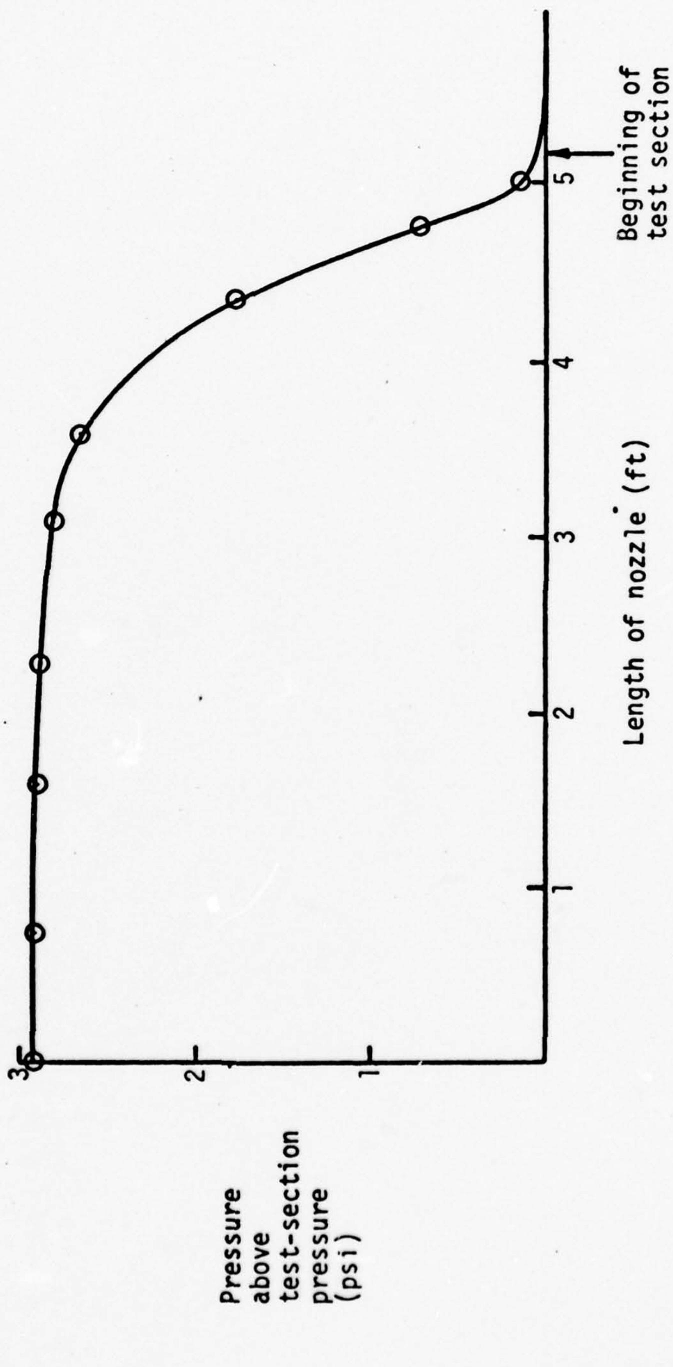


Figure 5 - Pressure vs Length in Nozzle

pressure back to that at which the control is set by removing air from the pressure regulation tank (PRT). As it does this the tank fills with water. This filling of the PRT removes some water from the tunnel and allows more air into the tunnel through the test section air taps. The reduction of the volume of water inside the tunnel probably has at least a small effect on the free surface configuration. How much effect there is and when and where it begins to show is not known.

The test section air taps must be kept open to have a free surface because a continuous supply of air is needed above the surface. If the supply is cut off, the air cavity is soon washed downstream and the test section fills with water. This problem was due only to the makeshift arrangement of the tunnel. In a more permanent situation the air supply would be integrated with the pressure control system and this problem should not be a factor.

As was mentioned before, the location of the free surface in the test section was not very stable. It fluctuated up and down at all but the lowest tunnel velocities. Also, the velocity readings for the tunnel test section varied widely at one speed setting. The test section pressure readings were also unstable due to the reasons just mentioned. It was thus impossible to firmly establish critical velocities and pressures.

The test section velocities were measured with a pitot static probe. When the tunnel was operating in the free surface mode the measured velocities were usually lower than the velocities noted on the RPM indicator on the control console. This is possibly due to additional head losses incurred by the existance of a hydraulic jump at some point.

The numerical velocities noted in this report and all references to a test section velocity are those measured with a pitot static probe.

The only conclusion that can be drawn from this week of testing was that for all sluice sizes the test section was flooded by a hydraulic jump at velocities above a mean of about 15 feet per second. At velocities approaching flooding velocity of the test section the quality of the water surface deteriorated significantly. A great deal of spray was present immediately above the surface, and the surface itself was very rough. Even at a given instant of time it was very difficult to determine within one half to three quarters of an inch where exactly the surface of the water was. In some cases it was difficult to see if there even was a distinct surface (see Figure 6). These disturbances were in addition to the fluctuation with time of the surface elevation.

Other potentially interesting information that was not immediately obtainable was the flow profile in the diffuser downstream of the test section. Often for considerable lengths of time, water was totally absent from the downstream vacuum dome located on top of the first turn. (See Figure 1) It was thus possible that at these times the free surface extended all the way down the diffuser to the first turn. Due to a total absence of windows in the diffuser, what exactly was happening inside was not known. Much of the flow phenomena such as the existence and location of a hydraulic jump, the depths of flow, and the effects of the first turn on the flow would be valuable. However, without visual access this qualitative information was unattainable.

IV. Initiation of Free Surface

The background study revealed the various methods for initiating a free surface used in other facilities. The possibility of using each of

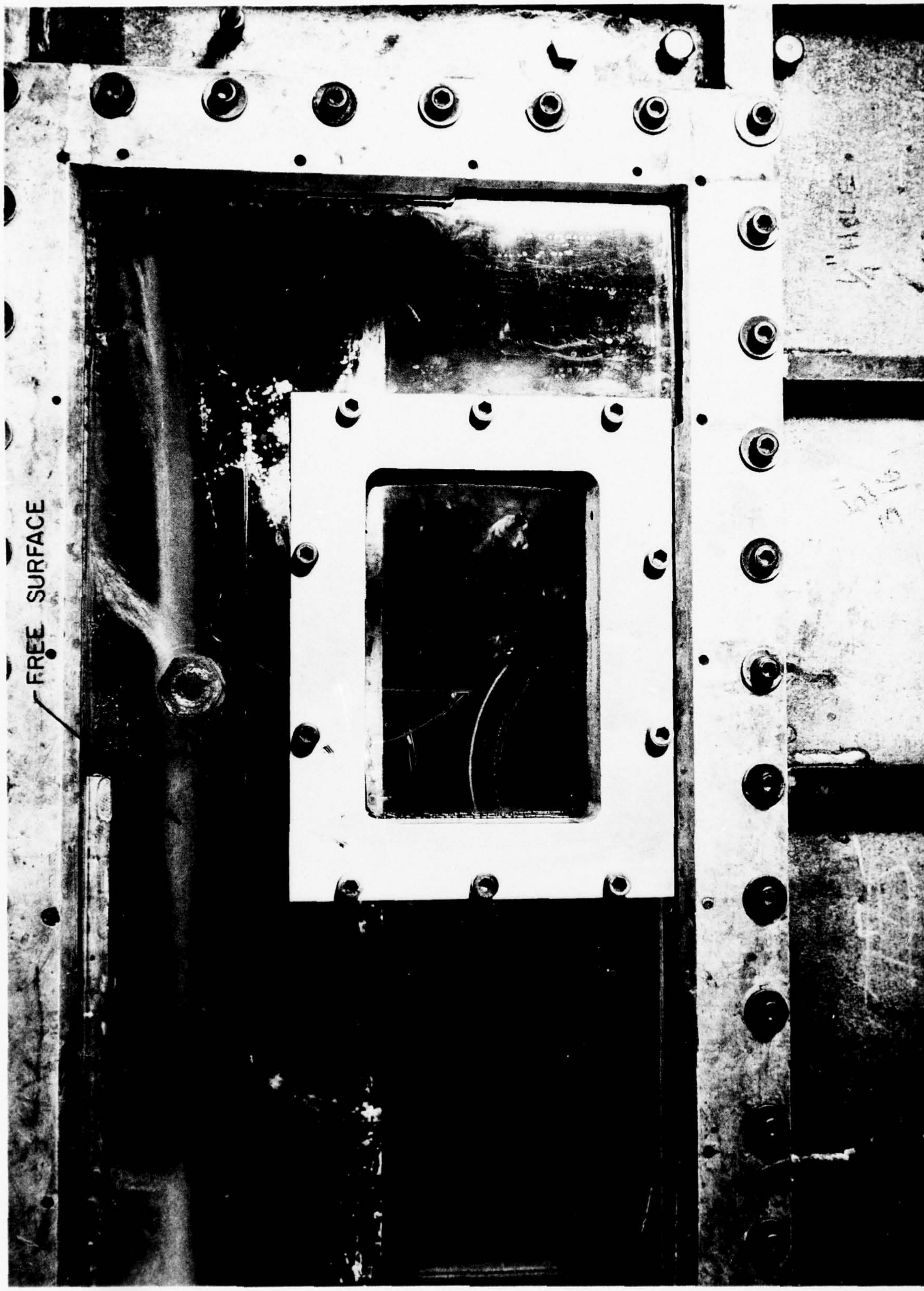


Figure 6 - Free Surface Flow

these types was studied. The sluice gate of Hydronautics was ruled out because of the resulting vena contracta. The sharp edged 30° nozzle of the St. Anthony Falls tunnel was also ruled out for the same reason. Due to our short test section almost zero vena contracta length could be allowed. The only way this could be done would be to have steady flow at the beginning of the test section. This requirement demanded that a full nozzle be used. The raised ceiling of the test section makes this even more attractive because the existing configuration could be used without modification to either the nozzle contours or the test section ceiling. The tunnel testing program showed that the vena contracta would probably not be a problem. Also, velocity profiles made during the testing program showed that the boundary layer which was experienced at the CIT tunnel would not be a problem here. The major dissatisfaction with the surface initiation during the testing program was the quality of the surface. Both with and without the sharp edged sluice pieces in the flow, the water surface was of poor quality.

It appeared during the tests that a portion of the surface disturbances was caused by sprays from the sluice piece corners and by water being forced by pressure to pass above and around the sluice piece, i.e., between the piece and the test section walls and ceiling (see Figure 7). What portion of the disturbances were caused by these effects isn't known. The elimination of these extraneous flows could be achieved by fitting a gasket or seal between the sluice piece and the tunnel. There is some hope that this would produce a better quality surface.

According to a study made before the design of the St. Anthony Falls Tunnel was complete [1], a sharp edge produced the best quality surface. It is on the basis of this study that the suggestion is made to use a

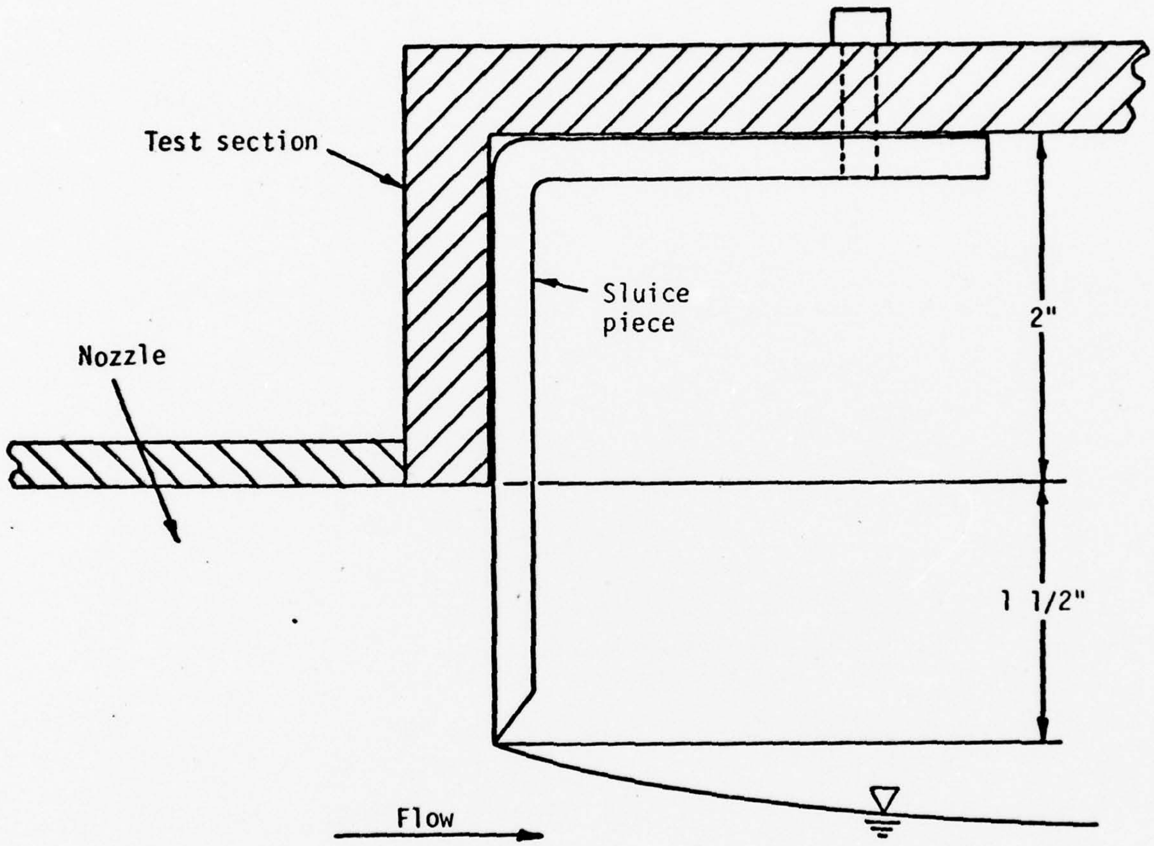


Figure 7 - Sluice Piece Mounting

sluice piece. A piece with a depth of about 1/4" produces little vena contracta.

V. Skimmer

A skimmer is frequently employed to terminate the free surface because it avoids the waste of the kinetic energy that occurs when the free surface is simply dumped into the downcomer or into a holding tank. If an efficient diffuser is used after the test section this kinetic energy can be recovered. This reduces the horsepower required to drive the tunnel. In addition, an efficient skimmer should stabilize the tailwater elevation and prevent a hydraulic jump from forming inside the test section. To make the transition from the test section to the diffuser, the skimmer separates the top layer of fluid from the rest of the stream. The bottom surface of the skimmer plate then becomes the top of the diffuser entrance. The fluid which is skimmed off of the main flow must be returned to the tunnel. It is suggested however that before this water is returned, it be deaerated.

The flow in the test section will be fairly turbulent and the water in the test section will be in contact with air. This situation will produce significant air entrainment in the fluid. The amount of air in the water will reach unacceptable levels fairly quickly if some means is not provided for its removal. The tunnel system as it exists now does have a small deaeration capability and this capability is in the process of being enlarged. The fluid is diverted out of the tunnel for the deaeration process. This diversion currently occurs at the end of the horizontal diffuser section. Since the flow is quite turbulent, the air is probably fairly well distributed through the water by the time it reaches this point. However, if the water to be run through the deaerator

was that water which was skimmed from the surface at the end of the air/water interface, this water would contain a greater than average quantity of air. The air will have had less time to diffuse through the water, and a greater concentration will exist near the surface. Thus the most heavily air entrained water is passed through the deaerator and more air is removed. This flow must be separated and returned to the main flow anyway so this seems to be a very logical solution to two problems.

Once the skimmed flow is separated from the main tunnel flow some means of exit from the tunnel casing must be provided. Two basic means are sketched in Figures 8 and 9. Figure 8 shows a simple arrangement which diverts the skimmed flow out through the tunnel sides. In Figure 9 the flow is shown being flipped up and out through the diffuser ceiling. Whether either of these basic plans is to be used or a different scheme devised, a few basic thoughts should be kept in mind. First, the size and shape of the exit must be sufficient to prevent a back-up of water into the test section. The divergence of flow in either of the schemes presented here might cause a hydraulic jump on the skimmer plate. This would be acceptable as long as it did not back-up into the test section. Secondly, the tunnel test section is bridged out from supports near its ends. A check should be made to ensure that any large holes cut in the tunnel casing leave enough structure intact to enable the tunnel to support itself and the water inside it.

Finally, it must be remembered that the tunnel must retain the capability to be converted back to a closed channel facility. Any holes put into the tunnel casing must be capable of being temporarily resealed in such a manner that a smooth surface can again be presented to the water flowing inside.

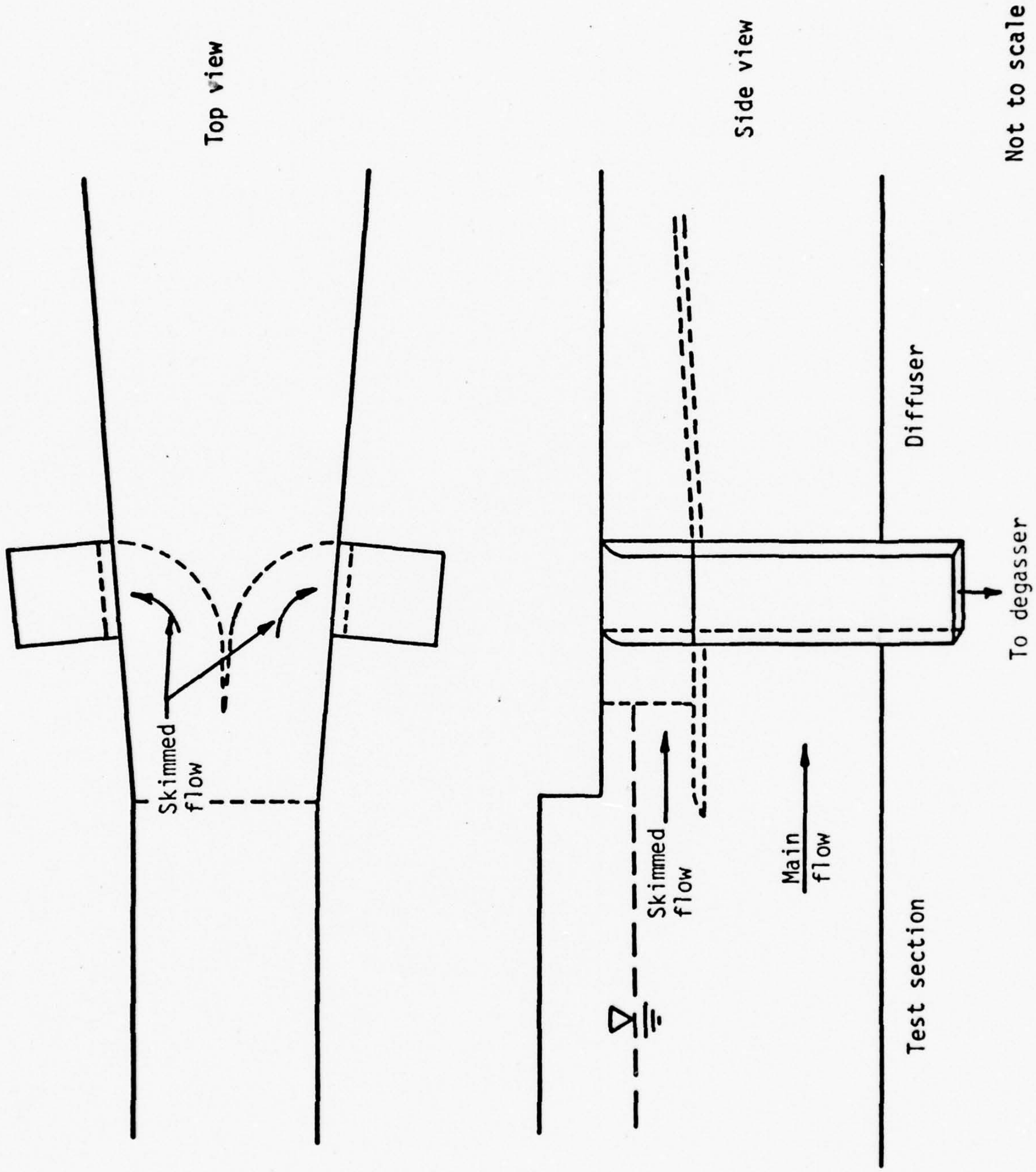


Figure 8 - Schematic of Skimmed Flow Exit - Method 1

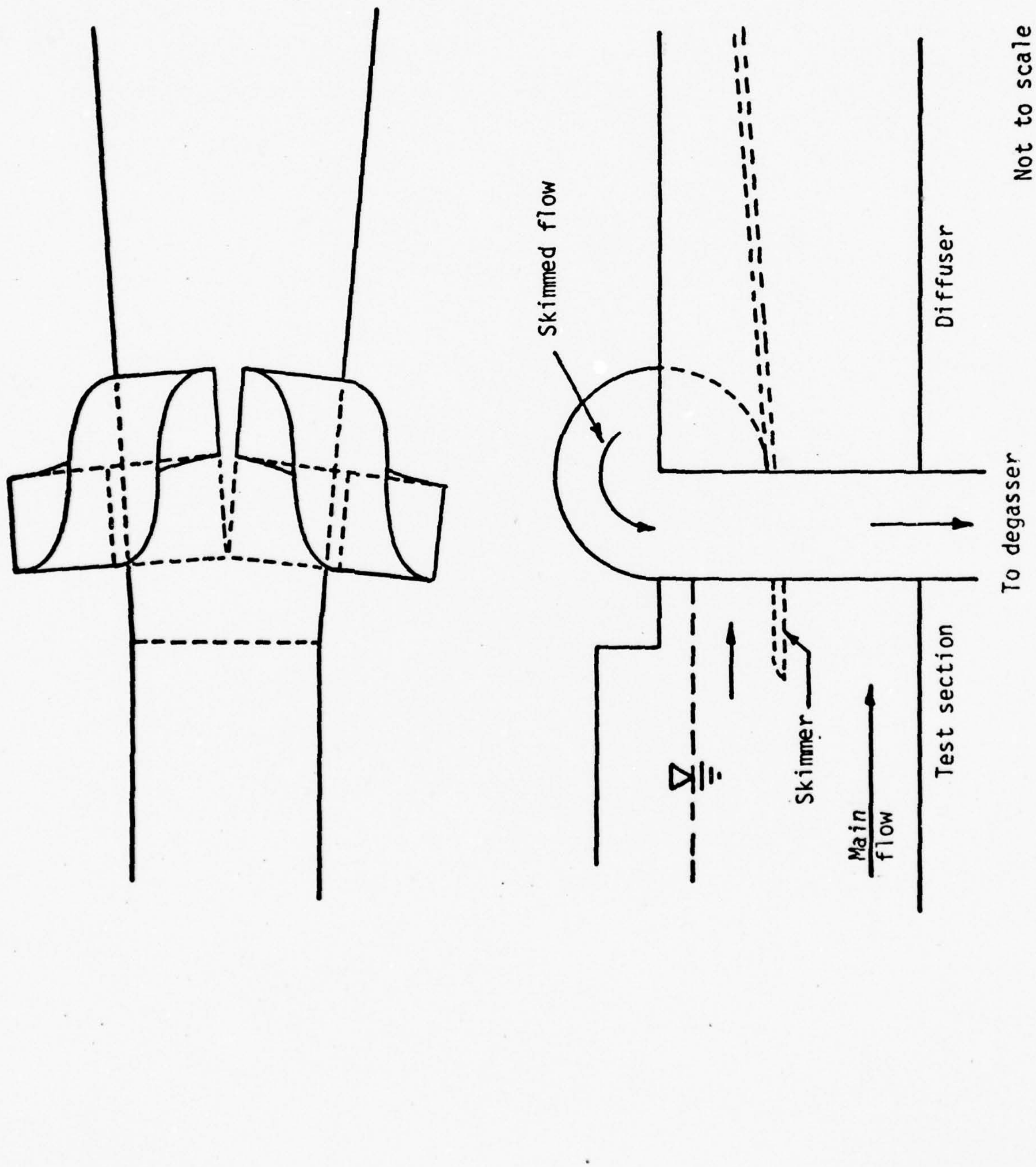


Figure 9 - Schematic of Skimmed Flow Exit - Method 2

Experience has shown that approximately 5 percent of the total flow should be skimmed [1]. For a test section velocity of 55 fps and a flow depth of 19 inches, 5% of the flow is 1.63 cfs. This requires a velocity of 19 fps in the new degassing system's 4" pipes. The deaeration chamber itself is the same one that is used by the large 48-inch water tunnel. It is large enough to handle the projected free surface tunnel deaeration flow. The primary lack of capacity in the system will be in the piping from the tunnel to the deaeration tanks. A larger pump and/or larger pipes will probably be necessary.

Some means will also have to be provided to supply air to the test section. This would probably be done best through a redesign of the pressure control system. The tunnel pressure control system, as it presently exists, is designed to control the pressure of an incompressible fluid. The pressure regulating tank, which is located below the tunnel, has a pressurized air cavity above a water surface. This tank is connected to the bottom leg of the water tunnel. With a compressible cavity of air above the test section any attempt to regulate tunnel pressure by changing the water pressure will cause the test section air cavity to change in volume. This will cause a change in the test section water level, which is not acceptable. To keep the same volume of air above the test section surface at varying pressures, some provision must be made to remove and supply air to the test section. The tunnel pressure will thus have to be controlled by a new pressure control system which operates by regulating the air pressure within the test section. The present system could be left intact for use when the tunnel is used as a closed channel tunnel.

Since air supply lines to the test section will be necessary for pressure control they will probably also work well for a continuous supply of air to the test section. This will be necessary to make up the air that is lost downstream with the water flow. The pressure control system designed for use in the 1971 GTWT proposal for a free surface water tunnel would be an excellent trial for such a design. With a few modifications that will be necessary to adapt the system to the rectangular rather than the circular test section, the system design could possibly be used as is. With this system, properly designed through coordination of pressure control and water level control, air could automatically be supplied to the test section air cavity at whatever rate is necessary for the existing operating conditions.

This brings up another aspect of the test section air-water relationship which should be given some consideration. That is water level control. The water in the test section will move at varying velocities and under varying pressures. Air will be continuously supplied to and removed from the test section. Water will continuously be skimmed from and returned to the tunnel. Through system lags a variation of water surface elevation is a conceivable possibility. If the water surface drops too low, it will go below the lip of the skimmer. This will cause the air cavity to move downstream into the diffuser and the diffuser efficiency to decrease. Along with this, air will become more heavily entrained in the water due to a larger air/water interface. In the meantime water will cease to flow to the deaeration chamber. Thus while air entrainment will be increased, air removal will cease. The surface drop will also cause air to flow into the piping system to the deaeration chamber. The consequences of this will depend on the design of that transport system, but with almost

any design at least some temporary problems will result. If the water surface rises too high in the test system, a hydraulic jump will form and the free surface will be lost.

It is foreseeable that the surface variations would be minor and that neither of these extremes would occur. If this is so, a water level control system will not be necessary. The slight variations might be made up for by the slightly varying volumes of water that would be skimmed from the surface. If however, a water level control system is deemed necessary the 1971 design could again provide a good starting point, if not the total final design.

Whether or not a water level control is necessary, proper positioning of the skimmer level is significant. Different problems are presented depending upon whether the skimmer is to be of a stationary or movable design. Making the skimmer level adjustable introduces several complications into the design, which are discussed here.

The end of the under surface of the skimmer is also the beginning of the diffuser section ceiling. If the skimmer is stationary, the ceiling of the diffuser can be simply an extension of the skimmer, (see Figure 10). If the skimmer is adjustable, one of several variations would have to be chosen. The diffuser could be made adjustable, or some sort of flexible coupling could be employed, or a discontinuity could be allowed to exist. To make an adjustable diffuser ceiling would require extensive modification of the present diffuser section. To have a ceiling piece which is able to move up and down, the walls of the diffuser would have to be parallel to each other in any plane perpendicular to the flow. In the present case the walls are parallel for the most part but at the top they angle towards each other due to the octagonally shaped cross-section of the diffuser.

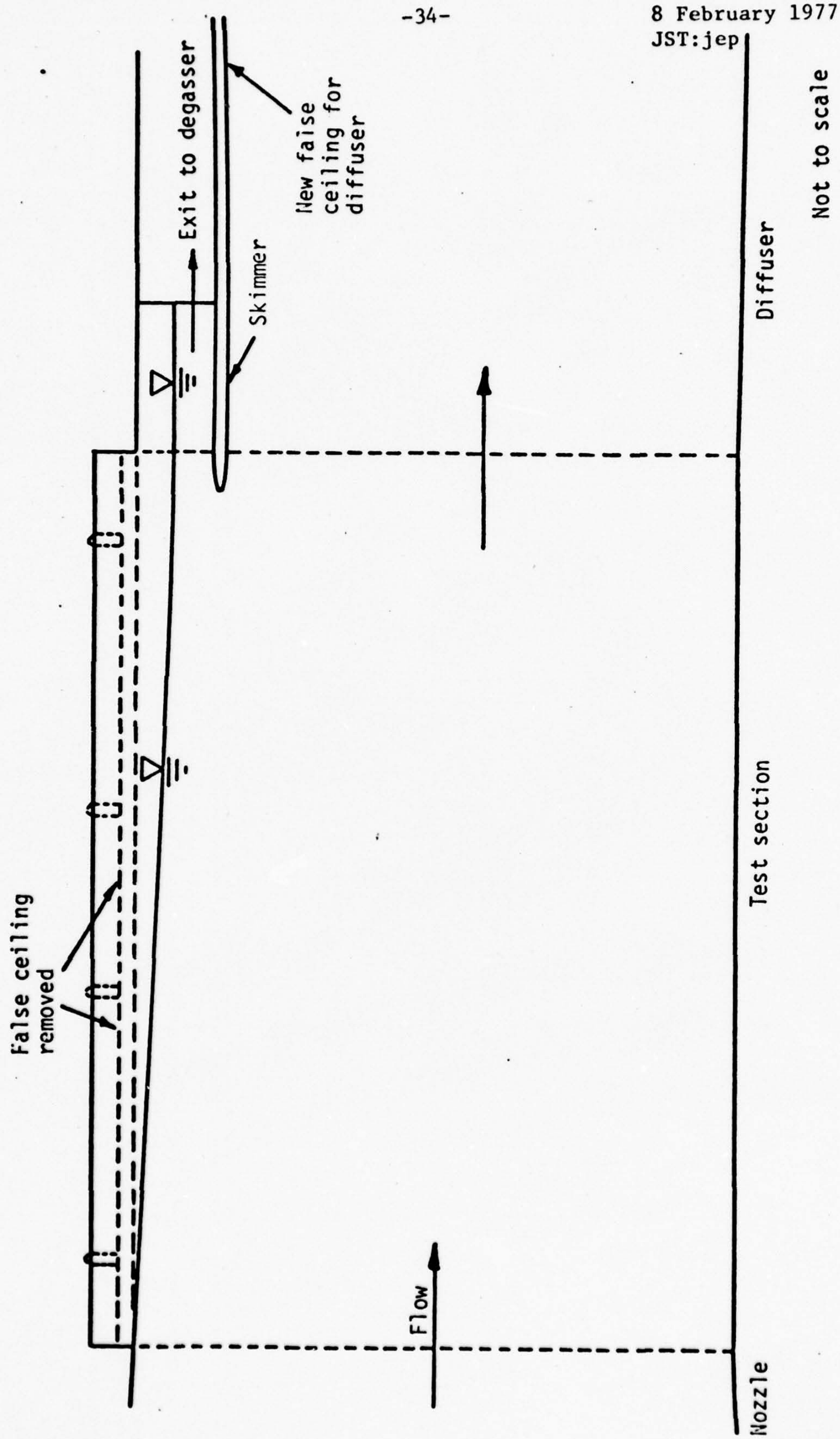


Figure 10 - Schematic of Test Section Side View

A possible variation of this scheme might be to have a partially adjustable ceiling. This could be adjustable from the skimmer back to some point near where the new diffuser ceiling intersects the angled sides. From this point to the end of the diffuser the ceiling would be stationary (see Figure 11). A flexible ceiling such as is in use at St. Anthony Falls [2] could also be used. Another solution would be to allow a discontinuity in the ceiling at the skimmer/diffuser junction. How large a discontinuity would result would depend on how adjustable the skimmer was. Another solution would be to make the skimmer movable in an arc pivoted at the skimmer/diffuser junction rather than have it move up and down parallel to the floor. No matter what type of skimmer/diffuser arrangement is used, it is important to remember that the capability to return the tunnel to its present closed channel configuration must be retained. Just as important as the relationship of the movable skimmer to the flow below it, is the relationship of the movable skimmer to the flow above it. Unless a hydraulic jump forms above the skimmer plate this will still be open channel flow. Any discontinuity could cause a hydraulic jump to form. Whether such a jump would propagate into the deeper water upstream in the test section has not been fully studied. In any case a smooth flow path should be provided for the high velocity, shallow depth skimmed flow.

Whether or not the skimmer is designed to be adjustable, proper positioning of it will be necessary to skim the proper amount of water from the surface. If the skimmer is adjustable, the final adjustments can of course be made during operation. However, the designer must make sure that the range of surface elevations can be covered by the adjustment range of the skimmer. If the skimmer is nonadjustable, the design should

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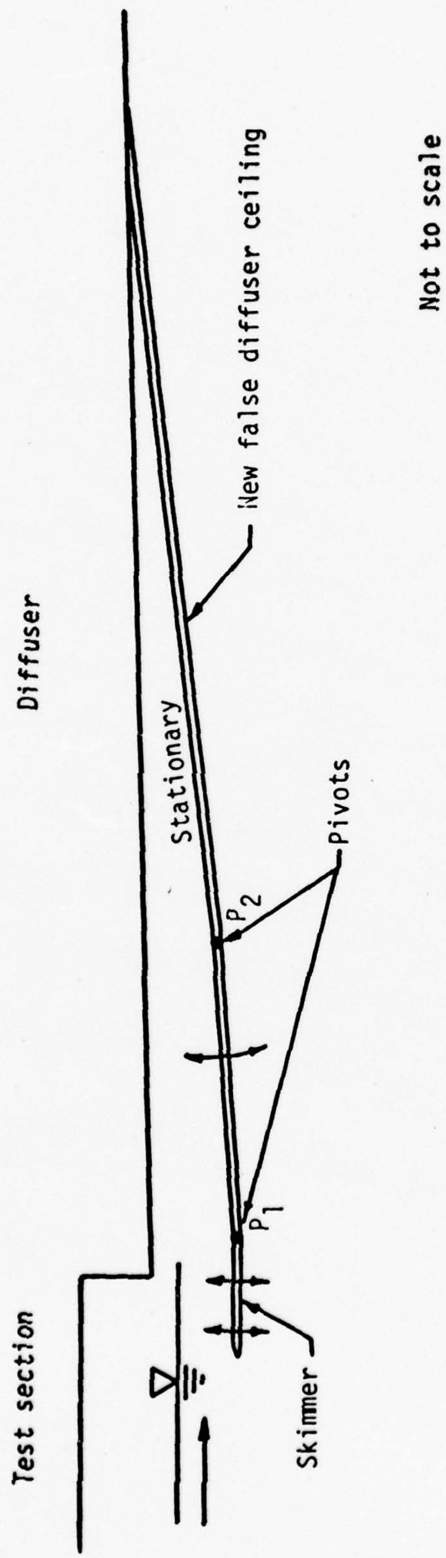

Figure 11 - One Possible Skimmer/Diffuser Arrangement

specify a skimmer elevation which has a height that will on the average skim off 5% of the flow [1]. This elevation will depend on the water surface profile.

VI. Other Design Considerations

Among the other design considerations within the test section is the remounting of the hydrofoil balance. As the balance is presently situated in the test section it enables foil shapes to be tested at only one depth relative to the test section. With a closed channel tunnel this is a tolerable situation. However, in a free surface tunnel the foil's depth below the water surface is an important variable and a fixed balance would greatly hinder the tunnel's research capabilities. The mounting of the balance must therefore be changed. If the balance is to be infinitely adjustable, slots would be necessary for the mounting bolts. A slot in the tunnel wall would also be necessary for the foil being tested to project into the tunnel. When redesigning the balance mounting, one must keep in mind the fact that the tunnel must remain air and water tight for both positive and negative pressures. If the balance is to be adjustable in only finite steps some other arrangement could possibly be used.

Downstream of the test section, modification must be made to the diffuser. In the design of a diffuser from scratch, careful attention must be paid to factors like the expansion ratio and the angle of diffusion. In this case though, we are locked into these factors by the already existing situation. Most of the diffuser should be usable as is. The only modification that should be necessary is to the ceiling of the diffuser downstream of the test section. The skimmer mechanism at the end of the test section will cause the ceiling of the tunnel flow to be lower than it presently is. The simplest solution would probably be to use a false

ceiling as a transition from the bottom of skimmer back up to the original diffuser ceiling. The arrangement of this false ceiling piece has previously been discussed (see Figure 11).

VII. Free Surface Flow

To be useful as a testing medium, the fluid flow should be uniform. In an open channel flow situation, uniform flow exists only at the normal depth [18]. With the horizontal floor of the test section, the normal depth is at infinity. Thus uniform open channel flow is impossible in the level bottomed test section. According to Manning's equation, if one were to introduce a slope to the test section to produce a normal depth at 19.5" with a velocity of 55 fps the slope would have to be almost 1.5. At 15 fps, it would be 0.109. First, it is obvious that the required slope changes with velocity and this necessitates an adjustable bottom. Secondly, the slopes, even at very low velocities, are quite steep. At high velocities they become unreasonable within the confines of the present test section. If the present test section is to be used the existence of varied flow must be accepted. The concept of totally replacing the entire test section has not been investigated but perhaps this idea should be given further consideration.

Assuming that the present test section and its nonuniform free surface flow are to be accepted, the next step is to decide if the resulting nonuniform flow is uniform enough to be used as a testing medium.

a. Vena Contracta

The first flow phenomenon which will affect the surface profile is the vena contracta effect. If no sluice piece is used at the beginning of the test section the vena contracta effect should b nil. For the cases of a one half inch, and a one and one half inch sluice piece, the

surface profile was computed [19] assuming that the vena contracta effect controlled throughout the test section. These calculations are found in Appendix II. The plots of these profiles, Figures 12 and 13, show the magnitude of the variation in depth through the test section. Even the small one half inch sluice piece produces a considerable nonuniformity in the flow. A vena contracta curve is asymptotic and theoretically extends to infinity [19]. In actuality, at some point the vena contracta will cease to control the water surface. Exactly where, if at all, in the test section the control is transferred has not been established, but at some point a standard H-3 Surface profile may begin to control.

b. <u>Critical Depth</u>

Open channel flow can be defined on the basis of the relation of the flow depth to certain reference depths. These are the critical depth and the normal depth. Critical depth for a given flow is that depth at which the flow velocity is exactly equal to the wave velocity. Critical depth itself is very difficult to achieve, but to define flow as being deeper or shallower than this depth is very helpful. Flows with depths shallower than critical are known as supercritical flows while those with depths greater than critical depth are known as subcritical flows. With the constant channel width as present in the tunnel test section, critical depth is a function of only the flow. For all but the lowest start up flows the critical depth is greater than the flow depth.

c. <u>Normal Depth</u>

The normal depth is a function of flow velocity, and channel width, slope and friction. For the case of the test section under consideration where slope equals zero, the normal depth is infinity. The actual depth is thus less than both the critical and the normal depths.

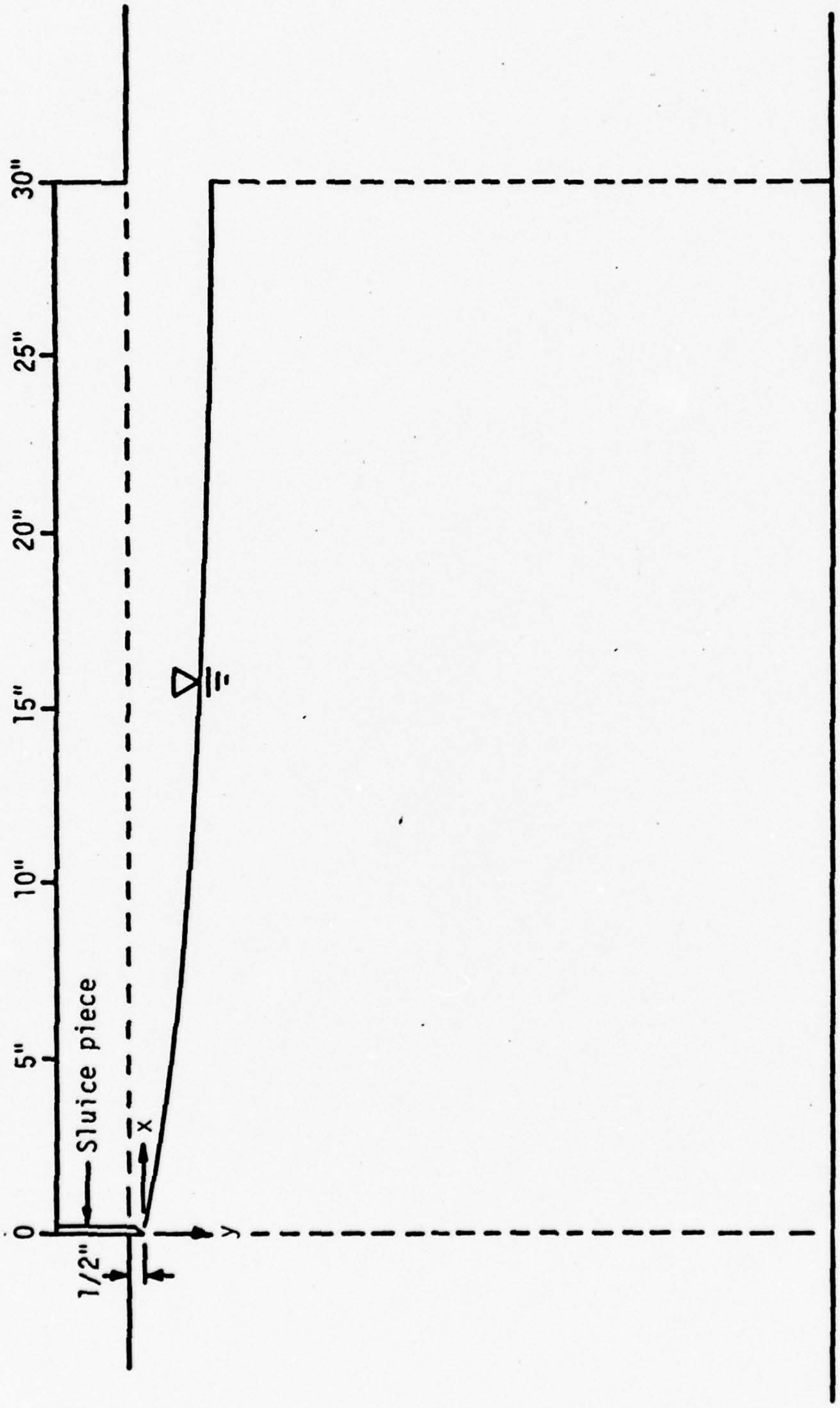

Figure 12 - Surface Profile - 1/2" Sluice Piece

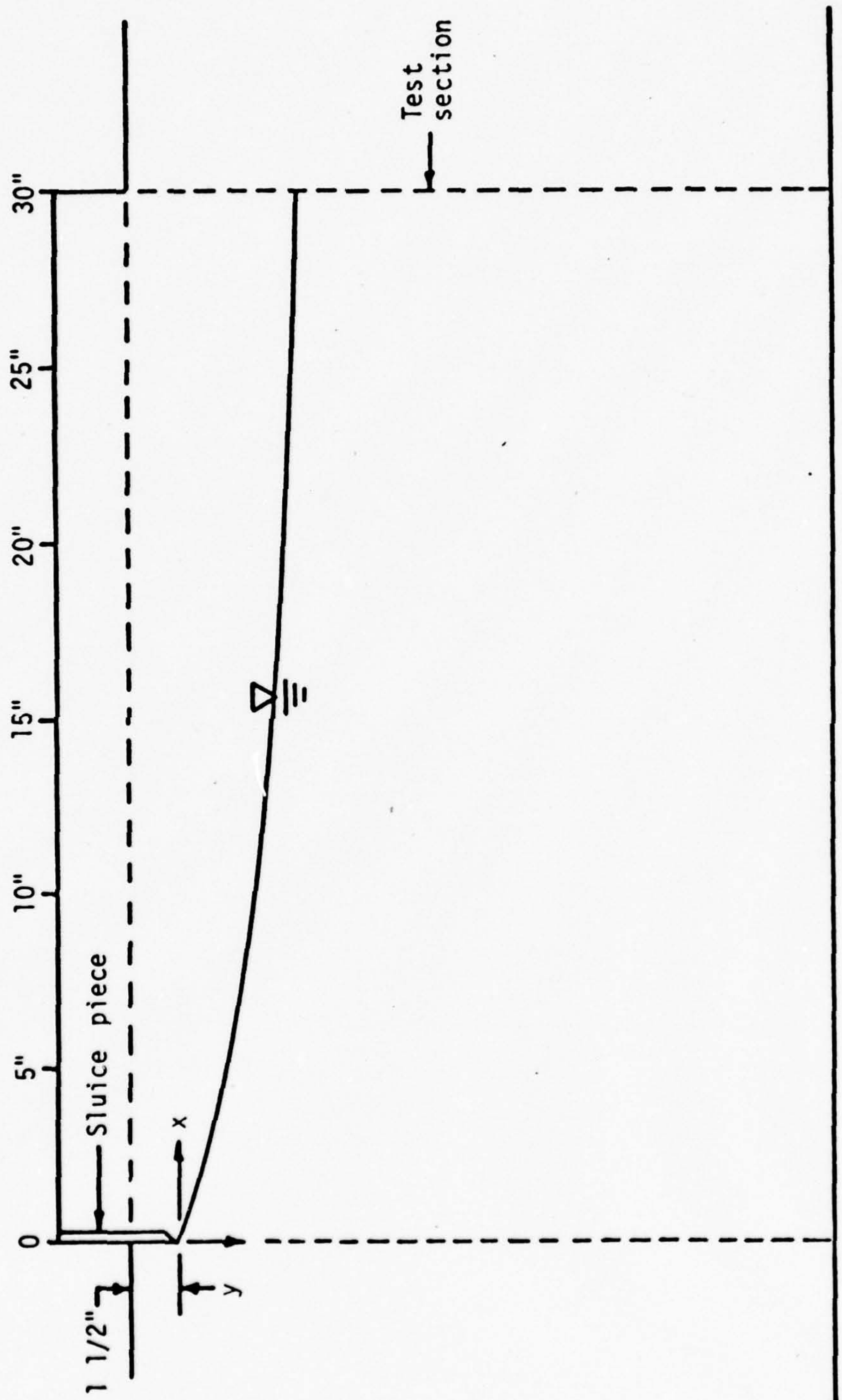

Figure 13 - Surface Profile - 1 1/2" Sluice Piece

d. H-3 Surface Profile

The surface profile for all flow conditions can be defined qualitatively on the basis of the relation between these two reference depths and the slope of the channel bottom. For this purpose, slopes are defined as being steep, critical, mild, horizontal, or adverse. With the existence of the zero test section slope and the flow depth situation as described above, the appropriate surface profile is known as an H-3 profile [18]. The general shape of an H-3 curve is shown in Figure 14.

To compute the surface profile, the formulas presented in Harrison's Discussion [20] of Chow's integration of the equation of gradually varied flow [21] were used. Since the point in the test section where the surface profile domination switches from the vena contracta to the H-3 profile is not known, a beginning depth had to be assumed. Depths of 18.5" and 19.5" were chosen at the beginning of the test section. That is, the same two sluice pieces (1/2" and 1 1/2") are to be used and the assumption is made that the H-3 profile overwhelms the vena contracta effect immediatley. The depth at the end of the test section was computed for these starting depths for two assumed initial velocities (see Table II).

TABLE II

Depths at End of Test Section, d_2, as a Function of Initial Depth, d_1, and Initial Velocity, V_1 [20]

	d_1	
V_1	18.5"	19.5"
20 fps	19.5"	20.4"
55 fps	19.1"	20.3"

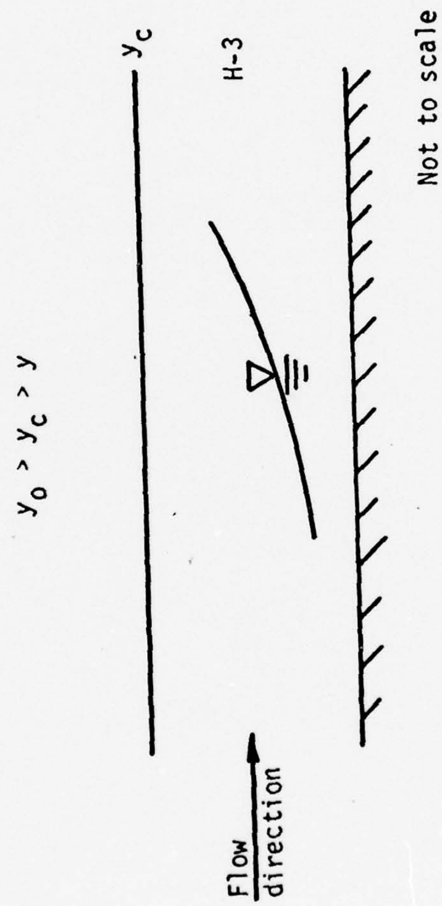

Figure 14 - General Shape - H-3 Surface Profile [18]

A sample calculation is present in Appendix III. On the average the water depth rose a little less than an inch through the length of the test section.

Some comments on these calculations are in order. First, it has been assumed that either one or the other of these two situations (vena contracta or H-3 curve) will dominate. It is possible that the surface drop due to the vena contracta and the surface rise due to the H-3 profile may be superimposed and cancel each other out, with a resulting relatively level surface. This is a risky basis upon which to assume uniform flow and although it may be possible, it shouldn't be depended upon.

Also worthy of note: the final depth for the H-3 profiles beginning at a 19.5" depth is deeper than the exit depth from the test section. The test section depth is 22" but the exit is only 20" high.

e. Hydraulic Jump

The impact of the water on this obstruction could very possibly trigger a hydraulic jump, which is the third factor which could affect the test section water surface configuration. Hopefully this will not be the case. If a jump does occur the conjugate depth, or depth to which the water will rise, will be deeper than the test section. The free surface will cease to exist. Since the flow in the test section is very highly supercritical with Froude numbers up to 6.8, a hydraulic jump is very possible. One of the prime design considerations should be to prevent a hydraulic jump from occurring. Efforts along this line have been very successful at the CIT Tunnel [22]. There, a standing wave or hydraulic jump is easily washed downstream as the velocity is increased. The velocity can then be reduced until the Froude number is as low as 1.001.

f. Tailwater Elevation

The fourth factor which could affect the test section surface profile is the tailwater depth in the diffuser and above the skimmer. Since the test section flow is always supercritical, downstream factors such as tailwater depth should not be able to have a direct effect on the surface profile. The only way an effect can be induced is if a high tailwater elevation induces a hydraulic jump. Since the diffuser flow will be closed channel flow this type of phenomenon is no longer a factor. However, it has been shown that a hydraulic jump in an enclosed channel can continue with its effect being manifest by a sharp pressure head rise instead of a water surface rise [23]. The applicability of this phenomenon is not totally understood for the advocated situation. The presence of the skimmer suddenly causes closed channel flow to exist below it and a much shallower open channel flow above. Factors governing the exact nature of such a transition have not been dealt with extensively in the literature. This is one area where some research time could be effectively devoted with respect to this project.

A final condition which could affect the test section flow is a choking effect. This occurs when the air cavity above the free surface theoretically extends downstream to infinity. This occurs at the lowest positive cavitation number which can be obtained for any particular constrained flow. In other words, for each nozzle/sluice piece combination, there might be a minimum cavitation number below which flow will not exist. Cavitation number is defined as such [24]:

$$\sigma = \frac{P_o - P_c}{1/2 \rho V_o^2} \quad .$$

This effect has not been looked at with respect to this tunnel. A study to determine the tunnel's capability in this area might be worthwhile.

g. Surface Reactions

The previous discussion dealt with how close the computed surface profile would be to a level standard. Also important may be the reaction of the surface. One of the reasons for the proposed tunnel conversion is to study the surface effects of an underwater foil. In the prototype situation the natural tendency for the disturbed water surface is to return to its previous relatively undisturbed state. For some testing programs a similiar situation may be desirable in the tunnel. In open channel flow this situation is uniform flow. The flow in the channel under disucssion will not be near uniform. It will be very supercritical, and will not tend to return to its previous undisturbed state but will tend to deform further along the lines of its surface profile. For example: If the vena contracta effect is prevalent in the test section, the foil's presence may very well immediately terminate this effect. In this case an H-3 profile could then exist downstream. If an H-3 profile is already dominating the profile of the surface, this profile might continue downstream but not necessarily by first returning to its undisturbed depth first. The water will have no reason to return to this undisturbed depth. The water is at this moment under the influence of hydraulic forces which are stronger than gravity. Evidence of this is found in the fact that its depth was already increasing, not stationary.

If a hydraulic jump is present in the test section, this condition already unacceptable for testing. However, an H-3 profile's rising surface is tending toward a hydraulic jump. The presence of a test foil

may be enough to trigger a jump where one wasn't present otherwise. The tests conducted have already shown a strong tendency toward the filling of the test section by a hydraulic jump, even in the obstruction free channel.

To have uniform supercritical flow in the test section there must be a slope to the floor. To use an example already sited a slope of 0.109 is required for a velocity as low as 20 fps. This means a drop of 3.27 inches in the 30 inch long test section. This is quite a steep slope, and even at this very low velocity is already pushing the limit of what would be a practical slope to introduce in the test section.

A decision must be made as to how uniform a flow will be required for most of the tests to be run in this tunnel. In most cases the lack of uniformity cited will probably not be critical. A check of the other free surface tunnels mentioned earlier reveals that similar situations would exist in all of them. Two of them also have level bottoms and the slope at the third is only 0.00694.

VIII. Summary and Conclusions

After May 1976, this project became inactive. The literature search is essentially complete and some design problems and possible solutions have been discussed. The nature of the free surface has also been considered. It has been concluded that the test section flow will not be uniform. However, this lack of uniformity will hopefully not be a major problem for most test situations.

Most of the design ideas which were discussed have not been tested under free surface conditions. This is due to the difficulty with the makeshift free surface and the lack of accessibility to the tunnel when it is operating. For the purpose of testing some of the components

mentioned in this paper it is suggested that use be made of a small, low velocity channel available in the Department of Civil Engineering's Hydraulics Laboratory here at Penn State. The hydraulic conditions of this channel are not very similar to those of the tunnel under consideration. However, the fluid in the channel is very accessible even during operation and the flow can be viewed from all angles at all times. It would thus make a good location for some preliminary design tests. It is suggested that if and when this study is to continue, such preliminary testing would be a good point at which to resume work.

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Appendix I

Pressure Readings as Taken During Testing
Pressure (ft of water)

Pressure Tap #	Closed Channel	Free Surface
1	11.80	10.97
2	11.69	10.29
3	10.61	6.05
4	10.57	5.83
5	12.01	11.09
6	11.87	11.02
1	11.80	10.97

Appendix II

The surface profile through the test section was computed assuming vena contracta effects controlled through the entire test section.

Case I

The calculations were first made for a 1/2" sluice piece constricting the flow.

Sluice = 1/2" deep
Undisturbed Flow Depth would be 20"
Therefore Initial Depth = 19.5"

The area ratio is thus

$$\frac{A}{A_o} = \frac{19.5(b)}{20.0(b)} = 0.975 \quad .$$

The coefficient of contraction was then taken as 0.89 from a plot of contraction coefficients vs area ratios from Robertson [25]. This yielded a final depth of

$$(0.89)(19.5") = 17.4" = d \quad .$$

The equations from Streeter are based on a vena contracta of a flow which is perpendicular to the primary flow direction at the sluice. Since in the case under study the flow leaves the sluice at some angle between 0° and 90°, it is first necessary to find how much of the curve will be needed for each case. The surface profile plot is based on a coordinate system which has its origin at the edge of the sluice piece. The coordinate equations are:

$$y = \frac{4d}{\pi} \sin^2 \frac{\theta}{2}$$

$$x = \frac{2d}{\pi} [\ell n \tan (45° + \frac{\theta}{2}) - \sin \theta]$$

The final x coordinate is computed on the basis of the assumption that the surface angle, θ, is equal to 90° when the final depth is reached. (Surface angles are measured relative to a vertical line.)

$$y = \frac{4(17.4)}{\pi} \sin^2 (\frac{-90°}{2})$$

$$y = 11.08 \quad .$$

Since the sluice gate depth, 19.5", is 2.1 inches higher than the final depth, 17.4", 2.1 inches is subtracted from the final y coordinate to find the initial y coordinate of the portion of the curve that will be used.

$$y_o = 11.08 - 2.1$$

$$y_o = 8.98$$

The initial surface angle if then computed by substituting the initial "y" value into the equation and the rest of the profile coordinates are computed from this point on. Before final plotting, the coordinates are converted to a new coordinate syste ($\Delta x, \Delta y$) whose origin is defined as the edge of the sluice piece.

θ (degrees)	x (in)	y (in)	Δx (in)	Δy (in)
-79.09	-15.1	8.98	0.0	0.0
-80.00	-16.1	9.15	1.0	-0.17
-85.00	-23.7	10.11	8.6	-1.13
-87.22	-30.1	10.54	15.0	-1.56
-89.00	-41.4	10.88	26.3	-1.90
-89.29	-45.2	10.94	30.1	-1.96

These results are plotted in Figure 12.

Case II

The same calculations were made assuming a 1 1/2 inch sluice piece

$$\frac{A}{A_o} = \frac{18.5}{20.0} = 0.925 \quad .$$

From Robertson this yields a C_C of 0.81.

$$0.81\ (18.5") = 15.0" = d$$

$$y = \frac{4(15)}{\pi} \sin^2 \left(\frac{-90°}{2}\right)$$

$$y = 9.55$$

$$y = 9.55 - (18.5 - 15.0)$$

$$y_o = 6.05$$

θ (degrees)	x (in)	y (in)	Δx (in)	Δy (in)
-68.50°	-7.0	6.05	0.0	0.0
-70.00°	-7.6	6.28	0.6	-0.23
-80.00°	-13.9	7.89	6.9	-1.84
-85.00°	-20.4	8.72	13.4	-2.67
-85.78°	-22.0	8.85	15.0	-2.80
-87.00°	-25.2	9.05	18.2	-3.00
-88.00°	-29.1	9.22	22.1	-3.17
-89.00°	-35.7	9.38	28.7	-3.33
-89.13°	-37.1	9.40	30.1	-3.35

The resulting surface profile is plotted in Figure 13.

Appendix III

Using Chow's Integration of the Equation of Gradually Varied Flow [21], the surface profile through the test section can be computed. As was stated in the main text the exact point in the test section where the vena contracta effect ceases to control surface elevation and the H-3 curve takes over is not known. Therefore, for computational purposes at a given flowrate, a depth was assumed at the beginning of the test section and the H-3 curve was assumed to control throughout the entire test section length. The computations as performed are based on Harrison's adaption [20] of Chow's formula.

A sample calculation is presented for the case of an initial depth of 19.5 inches on an initial velocity of 55 feet per second.

$$y_1 = 19.5'' = 1.625'$$

$$V_1 = 55 \text{ fps}$$

$$L = 30'' = 2.5'$$

$$b = 4.5'' = 0.375'$$

$$\frac{LS_c}{y_c} = [P(P_2,M,N) - P(P_1,M,N)]$$

$$P(P,M,N) = \frac{1}{N-M+1}P^{N-M+1} - \frac{1}{N+1}P^{N+1}$$

$$P = y/y_c$$

$$M = 3.00 \text{ (for rectangular channels)}$$

$$N = \frac{10}{3} - \frac{8}{3}\frac{(y/b)}{1 + 2(y/b)} = 2.14 \text{ (for } y = 19.5'')$$

$$y_c = \sqrt[3]{q^2/g}$$

$$q = Q/b$$

$$Q = VA = V_y b$$

$$y_c = \sqrt[3]{(V_y)^2/g}$$

$$y_c = \sqrt[3]{(55 \cdot 19.5/12)^2/32.2}$$

$$y_c = 6.28 \text{ ft}$$

$$R_c = \frac{A_c}{P_c}$$

$$R_c = \frac{6.28(0.375)}{2(6.28)+0.375}$$

$$R_c = 0.1821 \text{ ft}$$

$$V_c = \frac{V_y}{y_c}$$

$$V_c = \frac{55(1.625)}{6.28}$$

$$V_c = 14.23 \text{ fps}$$

Critical slope is computed using the Manning equation.

$$V_c = \frac{1.49}{n} R_c^{2/3} S_c^{1/2}$$

$$14.23 = \frac{1.49}{0.01} (0.1821)^{2/3} S_c^{1/2}$$

$$S_c = 0.0884$$

$$P_1 = \frac{y_1}{y_c} = \frac{1.625}{6.280} = 0.259$$

$$P(P_1,M,N) = \frac{1}{N-M+1} P_1^{N-M+1} - \frac{1}{N+1} P^{N+1}$$

$$= \frac{1}{2.14-3+1} (.259)^{2.14-3+1} - \frac{1}{2.14+1} (.259)^{2.14+1}$$

$$= 5.91$$

$$\frac{LS_c}{y_c} = [P(P_2,M,N) - P(P_1,M,N)]$$

$$\frac{2.5(0.0884)}{6.28} = [P(P_2,M,N) - 5.91]$$

$$P(P_2,M,N) = 5.95$$

$$P(P_2,M,N) = \frac{1}{.14} P_2^{.14} - \frac{1}{3.14} P_2^{3.14}$$

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$$P_2 = 0.27 = \frac{y}{y_c} = \frac{y}{6.28}$$

$$y = 1.70' = 20.3''$$

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